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Light ions fragmentation for medical and space application

E. Rapisarda(1)(2), C. Agodi(3), C. Battistoni(4), A. A. Blancato(3), L. Calabretta(3), G. A. P. Cirrone(3), G. Cuttone(3), M. De Napoli(3), F. Giacoppo(3), A. Mairani(4), M. C. Morone(5), D. Nicolosi(3), V. Patera(6), G. Raciti(7), F. Romano(3), P. Sala(4), A. Sciubba(6), C. Sfienti(7)(2) and S. Tropea(3)

(1) *Centro Siciliano di Fisica Nucleare e Struttura della Materia - Catania, Italy*
(2) *INFN, Sezione di Catania - Catania, Italy*
(3) *INFN, Laboratori Nazionali del Sud - Catania, Italy*
(4) *INFN, Sezione di Milano - Milano, Italy*
(5) *Università di Roma "Tor Vergata" - Rome, Italy*
(6) *Università di Roma "La Sapienza" - Rome, Italy*
(7) *Università di Catania - Catania, Italy*

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Summary. — Nuclear fragmentation complicates both spacecraft shielding design and treatment planning for radiotherapy. Hadron therapy treatments require very high precision on the dose deposition (±2.5% and ±1.1 mm) in order to keep the benefit of the precise ion's ballistic. The largest uncertainty on the physical dose deposition is due to ion's nuclear interaction through the traversed material. The nuclear interactions of the incident ions must also be taken into account in understanding and addressing the effects of galactic cosmic rays ions on humans and sensitive components in space. Today the simulation codes are not able to reproduce the fragmentation process with the required precision. In order to constraint the model within the codes and complete fragmentation cross section databases, experimental campaign has started since few years at LNS in Catania to study the fragmentation of ^{12}C on various target at intermediate energies. Measurements of energy and angular distributions of charged fragments, and double differential cross sections will be addressed. Preliminary results and future perspectives are reported.

PACS 87.53.-j – Effects of ionizing radiation on biological systems.
PACS 87.55.D- – Treatment planning.
PACS 25.70.Mn – Projectile and target fragmentation.

1. – Description

Protons and ion beams (mainly ^{12}C) of intermediate and relativistic energies are widely used nowadays for cancer treatments. Compared to conventional radiotherapy,

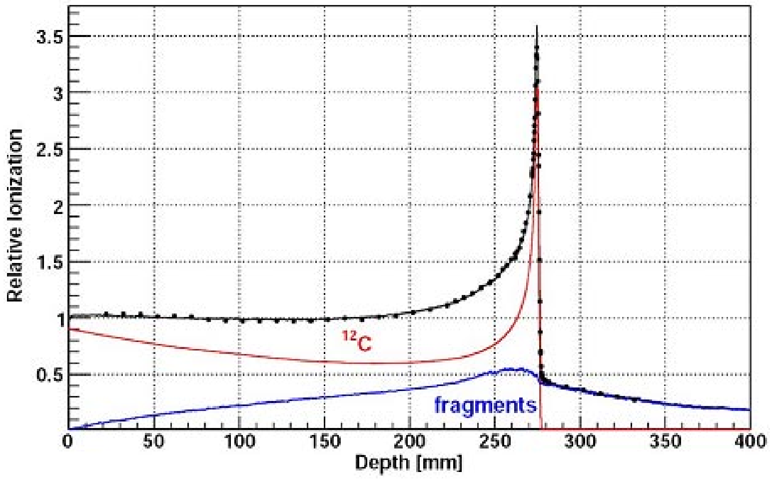

Fig. 1. – (Colour on-line) Monte Carlo simulation of the ionization induced by ^{12}C ions in water with (black line) and without (red line) activating nuclear reactions. The blue line represents the produced fragments ionization's contribution. Dots are experimental data.

hadrontherapy presents two main advantages: a maximum of dose deposition at the Bragg peak and, for ions heavier than protons, an enhanced biological effectiveness in the Bragg peak region. However along the penetration path in the patient tissue, the incident ions undergo nuclear interactions that, while reducing the number of incident ions, produce a wide spectrum of fragments ranging from the lighter ones up to the mass of the projectile. As a consequence, a non-negligible part of the dose is released in the surrounding tissues and a decrease of the dose at the tumor is seen, as shown in fig. 1. Normally less than 50% of the carbon projectiles actually reach the tumor in therapy, and this make very clear that a precise knowledge of the nuclear reaction effects is necessary for treatment planning [1].

Nuclear interaction in the medium substantially modifies also the radiation fields inside the spacecraft and must be carefully taken into account in the design of the spatial vehicles [2, 3]. Shielding is today considered the only practical and effective solution to protect humans and sensitive components from some of the hazards of space radiations, the major risk for crews in interplanetary mission. Spacecraft shielding design is extremely complicated by the production of secondary fragments, including neutrons and bremsstrahlung, generated in the nuclear interaction of the space radiation with the shielding material. In particular, the cascade of secondary particles can become very significant for heavy structures such as the Space Shuttle, the International Space Station, and the large observatories.

Measurements at particle accelerators can be used to evaluate fragmentation effects with well-defined beams and target with high statistics. Until relatively recently, most of the studies on nuclear fragmentation and transport models in matter were driven by the interests of the nuclear physics and later, of the hadron therapy communities. However the experimental and theoretical methods and the accelerator facilities developed for the use in heavy ion nuclear physics are directly applicable to radiotherapy and space radiation studies. While these measurements cannot simulate the complex radiation fields found in space, still they can be used to test fragmentation and radiation model performance for selected critical parameter sets: for specific projectile charges, masses and energies and target material and thickness.

Radiation transport computer codes, which simulate in detail the physical interactions of particles as they pass through matter, have been available for decades both in hadrotherapy and space radiation protection [4]. Such codes include deterministic codes: TRiP used by SIEMENS for hadrotherapy in Europe, HIBRAC used for carbon therapy in Japan and, HZETRN used by NASA for spacecraft shielding design; as well as Monte Carlo codes: FLUKA, GEANT4, SHIELD-HIT, and PHITS.

However the accuracy of these codes is not sufficient to obtain the precision (about 2.5%) on the deposited dose required by medical and space applications; the largest uncertainty coming from the physical models and the lack in the fragment production cross sections [5].

To guarantee the reliability and predictiveness of these codes in all domains of application, check and validation on precise experimental data (energy and angular distributions and production cross-sections for all the produced fragments) of the physical models included in the transport codes is therefore mandatory. In this context it becomes extremely important to perform extensive measurements of ^{12}C and heavy ions fragmentation reaction especially in the energy domain where lack of data exists or where the existing data do not have the required precision.

To improve the knowledge of ^{12}C fragmentation at intermediate energies we have started in 2006 an experimental campaign at LNS in Catania devoted to the measurements of production cross sections, energy spectra and angular distributions of fragments produced in ^{12}C fragmentation on thin ^{12}C, $^{\mathrm{nat}}$Pb and PMMA targets. In this paper we report some preliminary results on $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ at 62 MeV/nucleon.

2. – The experiment

The aim of the experiment performed at LNS in Catania is the measurement of production cross sections, energy spectra and angular distribution of light fragments produced in the collision of ^{12}C beam on thin ^{12}C, $^{\mathrm{nat}}$Pb and PMMA target and to compare the results with Monte Carlo simulations. The ^{12}C beam was delivered by the LNS Superconducting Cyclotron at incident energy of 62 MeV/nucleon. The detection system consisted on two Si-CsI hodoscopes with different granularity (fig. 2):

– 81 two-fold $1 \times 1\,\mathrm{cm}^2$ of active area telescopes: $300\,\mu$m Si detectors followed by a 10 cm long CsI(Tl),

– 88 three-fold $3 \times 3\,\mathrm{cm}^2$ of active area telescopes: $50\,\mu\mathrm{m} + 300\,\mu$m Si detectors followed by a 6 cm long CsI(Tl).

The implementation of the $50\,\mu$m ΔE detector in the telescopes set at larger angle allowed a lower energy threshold in the order of $3\,\mathrm{MeV}/u$. The first hodoscope covers, in steps of $\pm 0.6°$ both in θ and ϕ, the spherical surface around zero degree with an opening angle of $\pm 5°$. The second hodoscope covers, in steps of $\pm 1.5°$ both in θ and ϕ, the spherical surface having an opening angle between $\pm 5°$ and $\pm 21.5°$. A schematic view of the complete experimental setup is shown in fig. 2. The whole array covers 0.34 sr of the forward solid angle, including zero degree, with a geometrical efficiency of 72%. Its high granularity is suitable for accurate measurements of angular distributions. A typical inclusive ΔE-E plot from one of the telescopes at large angle is shown in fig. 3.

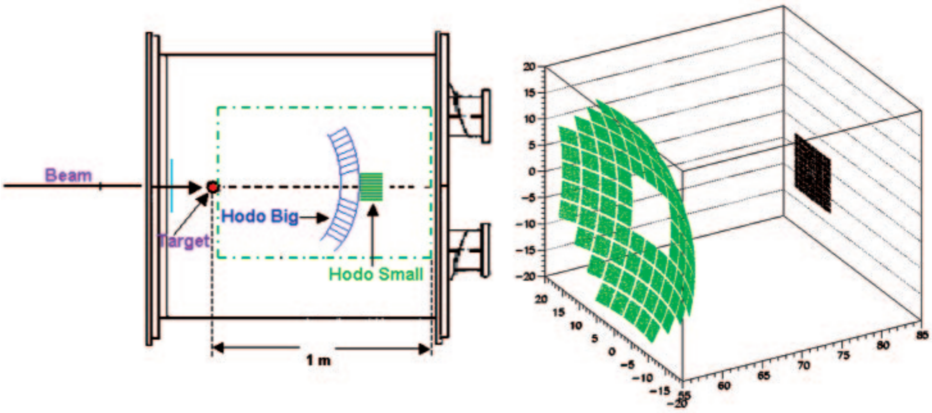

Fig. 2. – Left: schematic view of the detector setup in the scattering chamber. Right: 3D reconstruction of the hodoscopes geometry.

3. – Data analysis

Typical inclusive energy spectra for fragments detected at two different angles, $\theta = 2.75°$ and $\theta = 12.86°$, respectively, are shown in fig. 4 for $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ at 62 MeV/nucleon. The data display the well-known behavior of a bump centered at the projectile's velocity which is the typical feature of pure fragmentation reactions. The distributions however are not completely Gaussian but show a tail towards smaller energies. The contribution of the tail appears almost negligible at the smaller angle but becomes larger for larger scattering angle clearly showing an increased fragment emission from nuclear sources (mid-rapidity or target-like sources) other than the projectile. As expected in the intermediate energy regime, various reaction mechanisms (break-up, fusion, stripping in the continuum, deep-inelastic, etc., ...) are superimposed in the energy spectra with relative contributions depending on the incident energy and target.

3˙1. *Kinetic energy spectra.* – In order to gain qualitative insight and to provide reasonable extrapolation to unmeasured particle energies, the data were fitted with simple analytic functions.

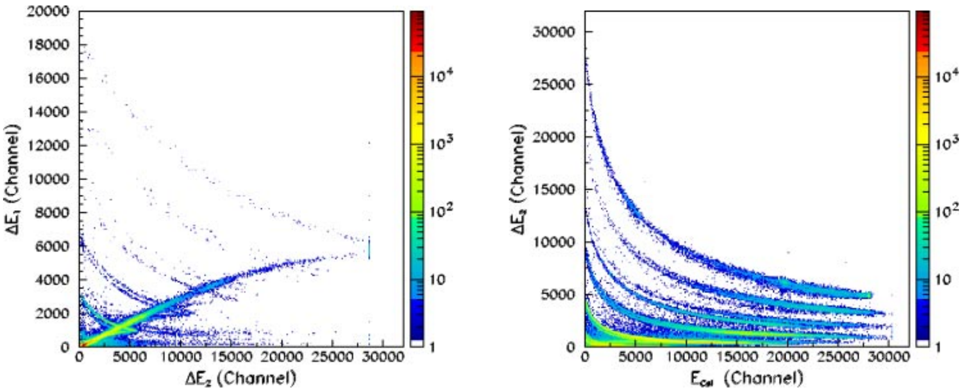

Fig. 3. – ΔE-E identification plots from one of the three-fold telescopes.

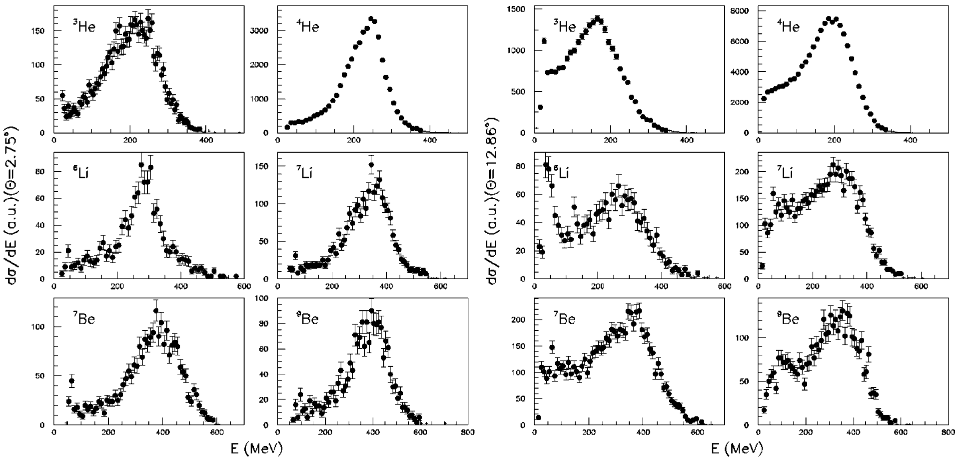

Fig. 4. – Kinetic energy spectra for fragments in the laboratory frame detected at different angles.

Fragment kinetic energy spectra in the laboratory frame for $3 \leq Z \leq 6$ can be rather well described by the superposition of two independent Gaussian distributions. Figure 5 shows an example of the fit procedure. The first Gaussian well reproduces the emission of a quasi-projectile source. The second Gaussian is introduced in order to obtain a satisfactory description of the energy spectra at low energy but its contribution is negligible confirming the previous hypothesis.

We have the caution, however, that the extracted parameters are not uniquely determined by our data and must not be over-interpreted since our measurements covered only a small range of emission angle. It is not the purpose of the present investigation to provide a unique interpretation of the single-particle reaction cross-sections. Nevertheless, the calculations indicate possible contributions from a number of different sources, *i.e.* the superposition of different reaction mechanisms, which cannot be disentangled without ambiguity.

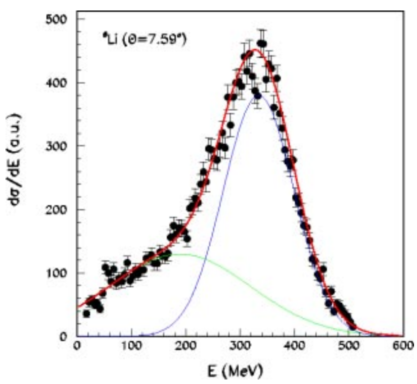

Fig. 5. – (Colour on-line) ^{6}Li kinetic energy spectrum for the ^{12}C + ^{12}C at 62 MeV/nucleon. The red line represent the fit with the superimposition of two independent Gaussian distributions (green and blue lines, respectively).

This two Gaussian component analysis and the physical interpretation is still subject of further analysis as well as the extraction of fragments production cross-sections and angular distributions.

4. – Conclusions and perspectives

A first experiments has been performed at LNS with a ^{12}C beams on thin ^{12}C, $^{\mathrm{nat}}$Pb and PMMA target at incident energy of 62 MeV/nucleon. The energy spectra show the superposition of different reaction mechanisms which cannot be easily disentangled. Analysis is still ongoing with the aim of extracting angular distributions and production cross-sections. Extensive comparisons with GEANT4 simulations are required in order to evaluate the accuracy of the different hadronic models implemented in the code in the description of this intermediate energy regime. The experimental results will be also compared with other Monte Carlo codes like FLUKA. These results will allow to complete the set of fragmentation production cross-sections required at energy lower than 100 MeV/nucleon.

In order to extend the measurements to relativistic energies, our collaboration has proposed a new experiment at GSI in Darmstadt using ^{12}C beams and heavy beams in the energy range 200–1000 MeV/nucleon. The experimental apparatus is a complex setup consisting of an upgrade version of the ALADiN, MUSIC-IV, ToF, LAND and Hodoscopes devices. This multidetector device will allow to detect charge and neutral fragments coming from the projectile fragmentation. Moreover, by using the ALADiN magnet, measurements of fragment emission at zero degree scattering angle will be achieved.

The full experimental program consists on measurements of ^{12}C fragmentation at 200, 400, and 1000 MeV/nucleon, on C and Au target, ^{16}O fragmentation at 200, 400 on C target, and ^{28}Si at 500 and 1000 MeV/nucleon on C and Si targets. We plan to start the first experiment in 2011.

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